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ANOMALOUS PLASMA DIFFUSION IN ION CYCLOTRON RESONANCE

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ABSTRACT

The phenomenon of heightened low-temperature plasma /145* diffusion across the lines of force of a constant uniform magnetic field, under conditions of high-frequency heating at a frequency close to the ion cyclotron frequency, is studied experimentally. The plasma was created in a glass tube by pulse discharge with electrons oscillating in hydrogen in a pressure range of 5×10^{-4} – 5×10^{-2} torr. The initial plasma density exceeded $1.7 \times 10^{13} \text{ cm}^{-3}$. An alternating current, which flowed along a spiral encircling a discharge tube, excited an electrical high-frequency field of 7.45×10^6 hertz and an axial period of 23 cm. The spiral and its attached condensers comprised an artificial line which was fed from a self-excited, pulse generator. In the

* Note: Numbers in the margin indicate pagination in the original foreign text.

magnetic field region, where high-frequency energy is strongly absorbed by the plasma because of ion cyclotron resonance, the plasma decay time decreases sharply, if the high-frequency current amplitude in the spiral exceeds a certain critical value which depends on the pressure of a neutral gas. Thus, ion diffusion across the forces lines of the magnetic field increases and random oscillations occur in the plasma. It has been experimentally established that at neutral gas pressures above 10^{-2} torr, the ratio of critical current strength to pressure remains constant. On this basis, it is assumed that anomalous diffusion occurs when the velocity of ion drift under the influence of an alternating azimuthal electric field rises above a critical value. This is possibly associated with "beam" instability. The possibility that "beam" instability will occur is apparently also corroborated - as the analysis shows - by the fact that the velocity acquired by an ion in an azimuthal electric field, at a current which is close to the critical value, in the interval between two collisions is in order of magnitude equal to the thermal velocity of the ions. It is noted that the investigated phenomenon of anomalous plasma diffusion in ion cyclotron resonance may be the cause of accelerated

plasma decay, in all devices where the plasma is heated by strong damping of the ion cyclotron wave in the region of ion cyclotron resonance and where considerable high-frequency power is fed into the plasma (Ref. 2, 3, 4).

1. Introduction

This paper deals with an experimental investigation of increased diffusion of a plasma which is located in a constant magnetic field and which is heated by a high-frequency field whose frequency is close to ion cyclotron frequency. A brief report (Ref. 1) contains preliminary data on accelerated plasma decay in ion cyclotron resonance.

So far as we know, all experiments using the phenomenon of strong damping of the ion cyclotron wave to heat plasma (Ref. 2, 3, 4) show that the plasma decays rapidly, in spite of being fed substantial amounts of high-frequency power (on the order of 100 kw or more) which is sufficient to heat the ions rapidly to high energies. Thus, in a work by Hooke et al. (Ref. 2), the gas breaks down when the high-frequency field is switched on, and the plasma density quickly rises. Thereafter, rapid plasma decay begins and lasts until the density falls to some optimum value, at which an ion cyclotron wave is generated. During generation of this wave, the decay rate decreases, but after wave-generation comes to an end, this velocity again rises. Plasma decay time is greatly dependent on initial gas pressure. This time becomes less than 100 microseconds at pressures on the order of 5×10^{-4} torr.

Nazarov et al. (Ref. 3) detected a rapid "disappearance" of plasma from the discharge tube, if the high-frequency power fed into it exceeded a certain critical value which depended on initial gas pressure and duration of the high-frequency voltage pulse applied to the coil.

Boley et al. (Ref. 4) did not directly measure the plasma. However, the authors state that measurements of both the magneto-hydrodynamic parameters of a wave excited in a plasma and of the input impedance of the system show that 800 microseconds after turning on the high-frequency generator, 1.7% of the initial amount of deuterium remains in the discharge chamber. (It was assumed in these experiments that the initial degree of plasma ionization, which was created before the high-frequency field was switched on as a special source, was close to 100%.)

The present work will show that anomalous diffusion across the lines of force of a constant magnetic field occurs in the low-temperature after-glow plasma, on which is imposed a high-frequency field with a frequency close to ion cyclotron frequency, if the amplitude of this field exceeds a certain critical value. This heightened diffusion, which causes accelerated plasma decay, is associated with the conversion of the plasma into a turbulent state with a broad spectrum of random oscillations. The data obtained make it possible to assume that this phenomenon occurs when ion drift in a direction perpendicular to the constant magnetic field reaches a definite value, which can be characterized by the

/146

ratio of the high-frequency field amplitude to the neutral gas pressure. This may possibly be associated with "beam" instability. We would like to note that Nazarov et al. made the same assumption in (Ref. 3).

2. Description of Apparatus. Measurement Methods.

We have elsewhere (Ref. 5) described in detail the apparatus in which plasma diffusion close to ion cyclotron resonance was investigated. The plasma was formed by impulsive discharge with oscillating electrons in hydrogen in a pressure range of 5×10^{-4} – 5×10^{-2} torr. The inside diameter of the glass discharge tube and the distance between electrodes were 6 cm and 88 cm, respectively. The intensity of the longitudinal quasi-constant magnetic field could be changed from 500 to 8000 gs.

The high-frequency field was excited in the plasma by an artificial LC-line with an inside spiral diameter of 7 cm. This line was fed from a pulse auto-generator of 7.45×10^6 hertz. The sector of the spiral connected with the plasma covered 2.5 lengths of the standing wave (the axial period of the high-frequency field was about 23 cm). As was shown in work (Ref. 5), the maximum high-frequency power imparted by the generator to the plasma under conditions of ion cyclotron resonance was 18 kw, with a plasma density of $1.7 \times 10^{13} \text{ cm}^{-3}$. The amplitude of the azimuthal high-frequency current j in the spiral was 30 a/cm. In the experiments described below, the generator was switched on after the discharge

current pulse was over, and j at maximum was 20 a/cm. Because of the low input line impedance, the amplitude of high-frequency voltage in the antinode of the standing wave was 1.6 kw in all. Supplementary heating of the plasma electrons and ionization of the neutral gas by a longitudinal, high-frequency electrical field E_z , which was connected with the longitudinal current component in the spiral, were insignificant in the most interesting measurement region of j . All the effects which will be described below remained unchanged when a so-called electrostatic screen - which substantially attenuated the field E_z in the space behind this screen - was placed between the spiral and the discharge tube.

The average (with respect to the cross-section of the discharge-tube) density n of the plasma electrons was measured with a very simple interferometer system for a wavelength of 8.1 mm. The transmitting and receiving horns were pointed at the plasma from a distance of 2 cm from the end of the spiral. Decay time τ was measured on oscillograms of the interference signal as the distance between two adjacent maxima (or minima). The quantities pertaining to a certain plasma density (saturation current at the probe, electron temperature) were measured for the density to which the interference signal minimum (or maximum) corresponded, which were situated between the extremes defining τ .

The ion diffusion current across the magnetic field was measured by a flat boundary probe, which represented a thin round molybdenum disk of 6 mm diameter. This was inserted into the discharge tube at

the spot where the density was being measured, and was fixed at the same level as the lateral surface of the tube. The probe had a negative potential of 100 v, relative to the cathodes of the plasma source, and operated under conditions of ion current saturation. Strictly speaking, the amplitude of this current should depend not only on the amplitude of the ion stream at the probe, but also on temperature T_e of the plasma electrons, being proportional to $T_e^{1/2}$. As will, however, be evident from what follows, in the most interesting cases it was possible, based on the saturation current magnitude, to make a qualitative estimate of the plasma diffusion rate across the magnetic field as a function of parameters, such as the magnetic field or high-frequency spiral current. This was due to the fact that, when these parameters were changed, the saturation current was able to change by more than an order of magnitude, while the electron temperature changed a maximum of five times.

The plasma electron temperature was calculated from the intensity of the H_β line in the discharge, at a given electron density and given neutral gas pressure. In the 1.7×10^{13} - $2.5 \times 10^{12} \text{ cm}^{-3}$ density range, which was measured by a radio interferometer, the main process responsible for emission of the line in the cold decaying plasma - when there is no high-frequency field - is electron recombination at an excited level (Ref. 6, 7). The work (Ref. 7) also demonstrated that this recombination was tripartite and they found an analytical expression for its coefficient, agreeing well with experimental results, as a function of n and T_e . When the high-

frequency field is switched on, the electrons are heated due to which the contribution to the intensity of line radiation - caused by recombination conversions ($\sim T_e^{-2}$) - decreases, and the intensity of radiation due to excitation by the electron collision increases. A calculation of intensity I_β of line H_β as a function of T_e at a given density of plasma and neutral atoms (the appropriate theoretical expression for I_β was derived by O. S. Pavlichenko) showed that under our conditions ($n \approx 5 \times 10^{12} \text{ cm}^{-3}$, initial electron temperature $\sim 0.1 \text{ ev}$, degree of ionization $\sim 1\%$), the function $I_\beta(T_e)$ at first rapidly decreased as T_e increased, passed through a minimum in the $T_e \approx 0.8 \text{ ev}$ region, and then again began to increase. The expression for the recombination factor in the computation was taken from work (Ref. 7), while appropriate expressions from (Ref. 8), averaged over the Maxwell distribution, were used as excitation and ionization /147 factors.

We also used the dependence $I_\beta(T_e)$ which was calculated in this way to compute the temperatures of the electrons in the plasma. It must be noted that the T_e determined in this way contains a certain indeterminacy caused by our lack of knowledge of the real energy distribution of the electrons in the plasma.

The intensity of H_β in the plasma was measured with an UM-2 monochromator and a FEU-19M photomultiplier.

3. Principal Experimental Results.

Our experiments in investigating anomalous plasma diffusion when the plasma was heated in ion cyclotron resonance may be divided into two groups. To the first group we assign the measurements which fixed the amplitude of the high-frequency field and measured the plasma decay time, ion saturation current for the probe, and other quantities as a function of the intensity of the constant magnetic field H .

Without a high-frequency field, the plasma decay time in the 1.7×10^{13} – $2.5 \times 10^{12} \text{ cm}^{-3}$ density range does not depend on H for $H \gtrsim 1.5 \text{ kg force}$. As (Ref. 9) points out, the explanation for this is that after-glow plasma density decrease in large magnetic fields is caused mainly by electron-ion recombination, not by diffusion.

Figure 1a shows the function $\tau(H)$ with the high-frequency field switched on. In these measurements, the initial hydrogen pressure was 10^{-2} torr, the high-frequency current amplitude in the spiral was 18 a/cm, and the time required for plasma density decrease from 1.1×10^{13} to $5.1 \times 10^{12} \text{ cm}^{-3}$ was taken as τ . As follows from the graph, as H increases, τ drastically decreases for $H \approx 4.5 \text{ kg force}$, and remains small up to $H \approx 6.5 \text{ kg force}$. It is known from (Ref. 5) that in this region of the magnetic fields, strong absorption of the high-frequency energy from ion cyclotron resonance occurs. (In all graphs, the broken vertical line denotes the field $H_0 = 4.9 \text{ kg force}$ corresponding to the cyclotron resonance of a solitary ion at the generator frequency.) Under the conditions described, the maximum absorption power was approximately 3 kw at a density of $7.6 \times 10^{12} \text{ cm}^{-3}$.

Figure 1b shows the dependence of the ion current J_i of saturation at the probe on the magnetic field strength at the density $7.6 \times 10^{12} \text{ cm}^{-3}$. In the region of the magnetic fields where τ is small, there is a substantial increase in the ion diffusion stream across the magnetic field.

We must note (as will be stated in more detail below) that the current pulse at the probe under conditions of heightened diffusion was made up of a constant component, on which were imposed random noises (low-frequency as compared to generator frequency) whose amplitude could amount to 50% of the total impulse magnitude. The sum of the constant component and the mean amplitude of the noises in the vicinity of a point of given density was used as J_i . The value of J_i was averaged over several (up to five) oscillograms.

In Figure 1c, the amplitude of the above-mentioned noises in /148 the vicinity of a point having the density $7.6 \times 10^{12} \text{ cm}^{-3}$ is plotted as a function of H .

Finally, Figures 1d and 1e show the intensity I_β of line H_β as a function of magnetic field strength and the thus-computed curve $T_e(H)$ for a plasma density of $7.6 \times 10^{12} \text{ cm}^{-3}$. As was to be expected, the plasma is heated considerably in the magnetic field region which is somewhat higher than H_0 , because of the absorption of high-frequency energy.

It thus follows from the above data that plasma decay time in the magnetic field region, where this plasma vigorously absorbs high-frequency energy, substantially decreased - despite the increase in

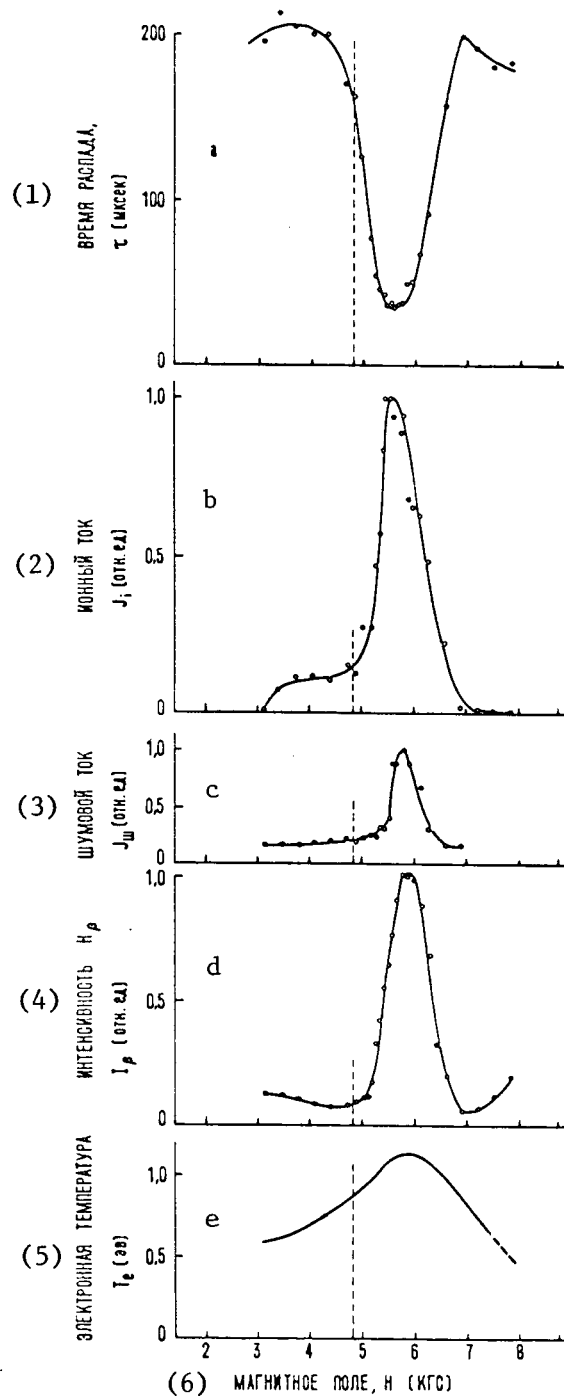


Figure 1

Dependence of Magnetic Field on (a) Decay Time, (b) Ion Current, (c) Noise Current, (d) H_β Line Strength, and (e) Electron Temperature at a Given High-Frequency Field Amplitude.

(1)-Decay Time, τ (microseconds); (2)-Ion Current, J_i (relative units); (3)-Noise Current, J_n (relative units); (4) H_β Strength, I_β (relative units); (5)-Electron Temperature, T_e (ev); (6)-Magnetic Field, H (kg force)

plasma temperature. It would seem that the deionization time ought also to increase, since the recombination rate drops. The fact that the ion saturation current at the boundary probe simultaneously increases as the decay time decreases indicates that the cause of this accelerated decay is heightened plasma diffusion across the magnetic field lines of force, as a result of the high-frequency field heating of the plasma. Finally, the intense noises attending this accelerated decay enables us to assume that the increased diffusion is caused by plasma instability in the high-frequency field.

Figure 2 gives functions $\tau(H)$ measured at different amplitude values of the high-frequency current in the spiral. These measurements were also made at a pressure of 10^{-2} torr, but the time required for the density to decrease from 7.6×10^{12} to $2.5 \times 10^{12} \text{ cm}^{-3}$ was adopted as τ . The high-frequency current amplitudes, at which these dependences were recorded, are indicated in the figures for each curve. Plasma decay time for all values of j increases as the magnetic field approaches H_0 , because of reduced electron recombination as T_e rises. However, for $j \approx 3 \text{ a/cm}$ "deformation" of the $\tau(H)$ curve begins, which is connected with the appearance of increased diffusion. As the high-frequency current rises further, a constantly deepening "dip" appears on the $\tau(H)$ curves in the magnetic field region where the high-frequency power absorbed by the plasma is maximum.

To the second group we shall assign the measurements which recorded the dependences of decay time, ion current at the probe, and H_β intensity on high-frequency field magnitude for a fixed magnetic

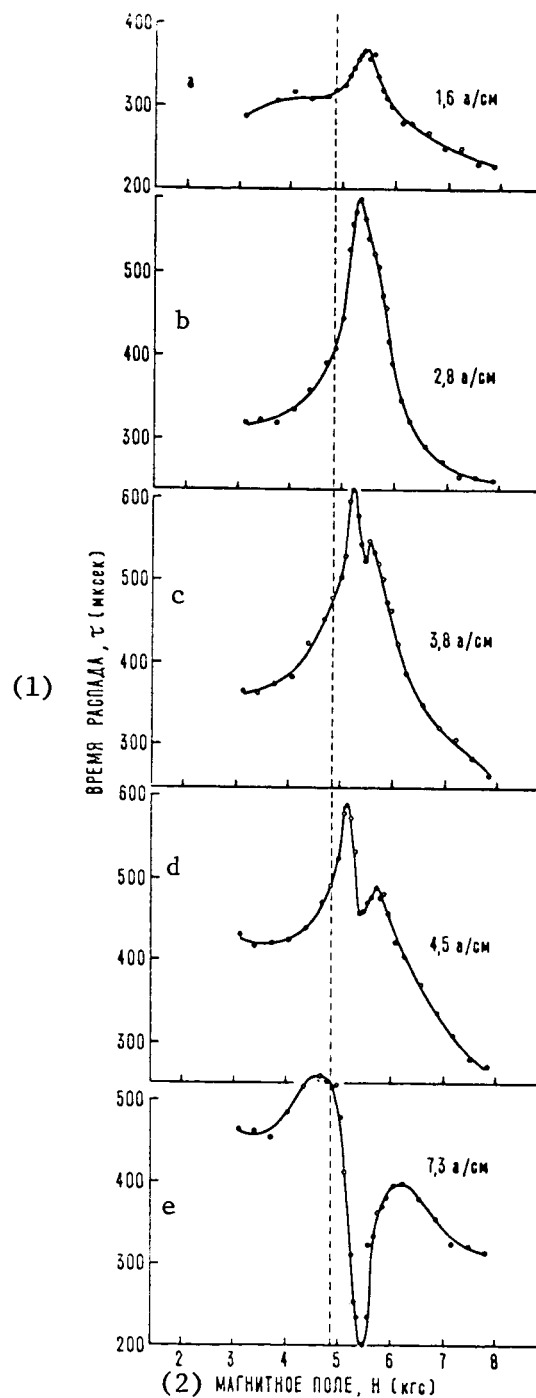


Figure 2

Dependence of Decay Time on Magnetic Field for Different Current Values in the Spiral

(1)-Decay Time, τ (microseconds); (2)-Magnetic Field, H (kg force)

field. Figure 3 shows dependences of this type. Hydrogen pressure in these measurements was 5×10^{-3} torr. The time required by the plasma density to drop from 1.1×10^{13} to $5.1 \times 10^{12} \text{ cm}^{-3}$ was used as τ . The constant magnetic field was fixed at the 5.6 kg force point, where the decay rate in this density range was maximum. The high-frequency current amplitude j was plotted on the horizontal axes.

The dependence of $\tau(j)$ is plotted in Figure 3a. As the spiral current increases, the decay time first increases because of plasma heating, and then - when the high-frequency current reaches a certain critical value of j_c (2.2 a/cm under the given conditions) - the decay time begins to decrease.

Figure 3b shows the dependence on j of the ion saturation current at the probe at a density of $7.6 \times 10^{12} \text{ cm}^{-3}$. In the $j \approx j_c$ region, the monotonic increase of J_i begins as j increases, while for $j \gtrsim 5 \text{ a/cm}$ the dependence of $J_i(j)$ is represented by a straight line which /149 is inclined toward the horizontal axis within the limits of measurement error. It is interesting to note that, if extended toward the region of decreasing j , this straight line intersects the horizontal axis at the point $j \approx j_c$.

In the examination of the dependence of $\tau(j)$, it is evident that with large enough values of j , the rate at which τ decreases is retarded, and tends towards a certain saturation on the order of 50 microseconds. At the same time, diffusion current continues to rise. We may therefore assume that decay τ is retarded for large high-

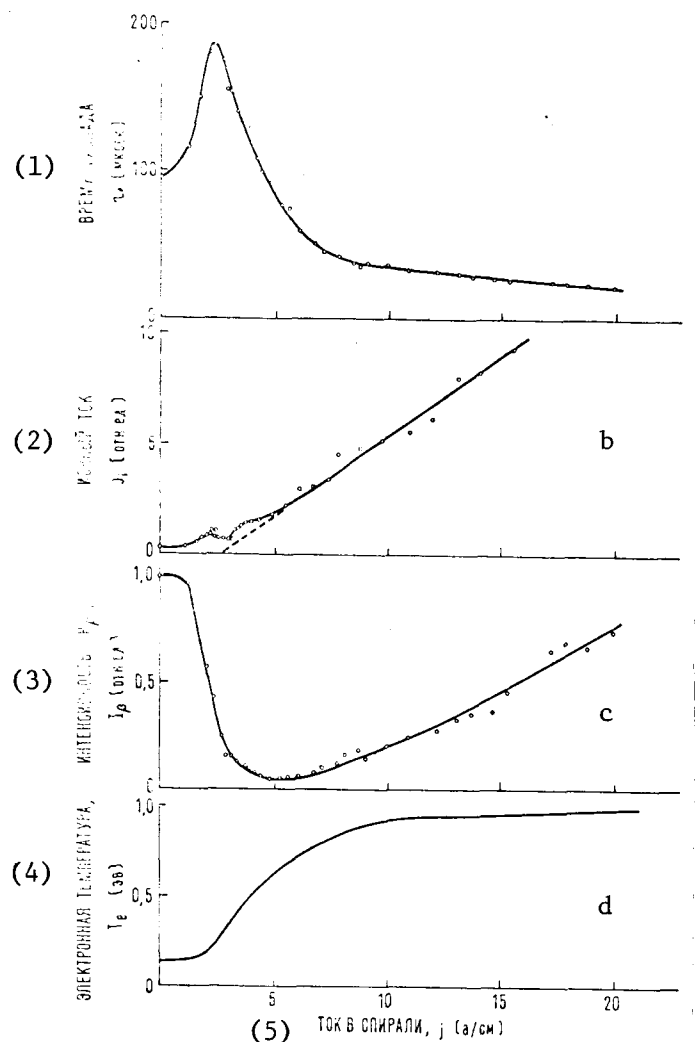


Figure 3

High-Frequency Field Amplitude as a Function of (a) Decay Time, (b) Ion Current, (c) H_β Line Intensity and (d) Electron Temperature for a Given Magnetic Field.

(1)-Decay Time, τ (microseconds); (2)-Ion Current, J_i (relative units); (3)- H_β Intensity, I_β (relative units); (4)-Electron Temperature, T_e (ev); (5)-Current in Spiral, j (a/cm)

frequency field amplitudes because of the ionization of the neutral gas, which partially compensates for the rapid decrease in plasma density resulting from diffusion. Computations show that gas ionization under our conditions must exert a marked effect on τ at an electron tempera-

ture on the order of 1 ev. This temperature is actually reached at resonance for large high-frequency fields. The dependence of H_β line emission strength on j at a density of $7.6 \times 10^{12} \text{ cm}^{-3}$, and the T_e values computed from this strength, are represented in Figure 3c and 3d.

The graphs of Figure 4 give a few $\tau(j)$ curves, recorded at different pressures. Plasma decay time was measured from 7.6×10^{12} to $2.5 \times 10^{12} \text{ cm}^{-3}$ for $H = 5.6 \text{ kg force}$. Just as its rise for $j < j_c$, so the decrease of τ for $j > j_c$ proceeds faster, the lower the pressure.

The upper section of Figure 4 gives the dependence of $j_c(p)$, where p is neutral gas pressure. When $p \gtrsim 10^{-2} \text{ torr}$, this dependence is obviously represented by a straight line and the ratio

$$j_c/p = \text{const} \quad (1)$$

holds.

The practical significance of this is that anomalous diffusion has its start at a certain ion drift rate in the plasma.

For magnetic field strengths differing from those in which the greatest plasma absorption of high-frequency energy occurs, the dependence of $\tau(j)$ is of the same nature as in Figure 4. However, in this case, increased diffusion begins at a greater high-frequency spiral current, while plasma decay for $j > j_c$ decreases more slowly. The above is illustrated by Figure 5, which presents two dependences of $\tau(j)$, one measured for $H = 5.6 \text{ kg force}$ (curve with a sharp maximum) and the other for $H = 3.75 \text{ kg force}$. Both curves are recorded at a hydrogen pressure of 10^{-2} torr , while the time required for

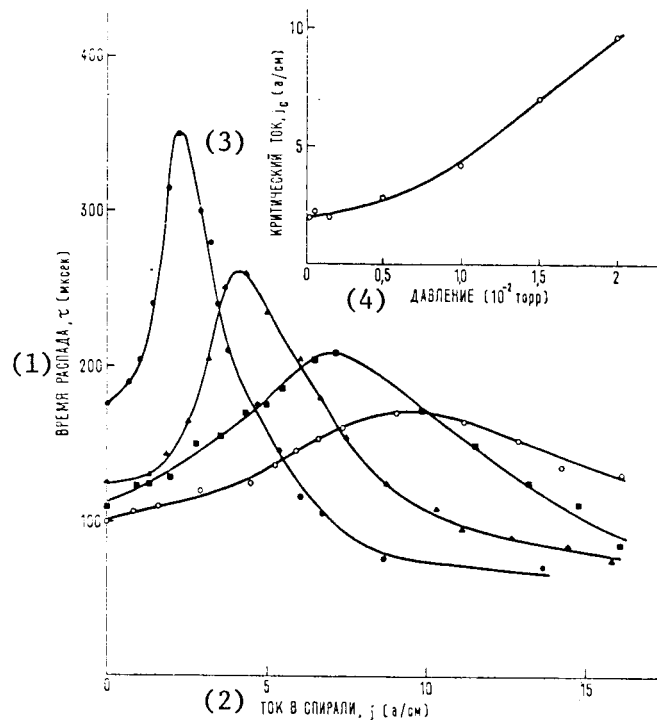


Figure 4

Decay Time as a Function of Current in Spiral with Respect to Pressure:
 ● - $p = 5 \times 10^{-3}$ torr; ▲ - 1.5×10^{-2} ; ■ - 1.5×10^{-2} ;
 ○ - 2×10^{-2} . The Upper Figure Gives the Dependence of Critical
 Current on Neutral Gas Pressure.

(1)-Decay Time, τ (microseconds); (2)-Current in Spiral j (a/cm);
 (3)-Critical Current, j_c (a/cm); (4)-Pressure (10^{-2} torr)

density to decrease from 7.6×10^{12} to $2.5 \times 10^{12} \text{ cm}^{-3}$ is used as τ .

As was already noted above, the decrease in plasma decay time and /150
 the increase in diffusion across the magnetic field is accompanied by
 intense random oscillations of the ion current at the probe. Figure 6
 (lower ray) gives a typical ion current oscillogram recorded for
 $H = 5.6 \text{ kg}$ force and $j = 20 \text{ a/cm}$. The high-frequency line voltage is
 fed to the input of the upper ray. Scanning period is 1000 microseconds.

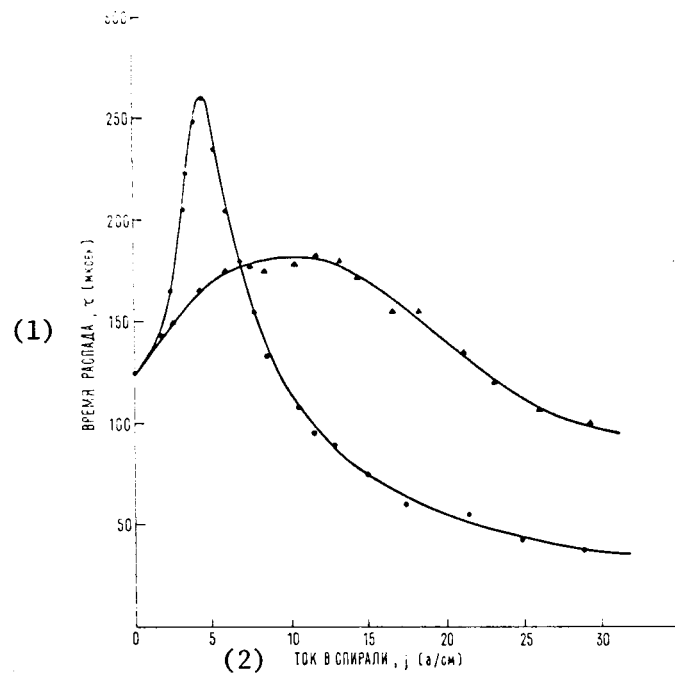


Figure 5

Decay Time as a Function of Spiral Current for $H = 5.6$ kg force (Curve with Sharp Maximum) and $H = 3.75$ kg force.

(1)-Decay Time, τ (microseconds); (2)-Spiral Current, j (a/cm)

The maximum value of the ion current for large plasma densities is "killed" by the oscillograph amplifier when scanning begins. The ion current pulse at the probe was led to the oscillograph input through a low-frequency filter with a 10^6 hertz frequency cutoff.

The turbulent state of the plasma in a strong high-frequency field and a constant magnetic field, which is somewhat higher than H_0 , may also be determined from the oscillogram forms of the interference signal. Figure 7b shows such an oscillogram recorded for $j > j_c$. For purposes of comparison, Figure 7a gives an interference pattern obtained for $j < j_c$, i.e., for a "quiet" plasma.

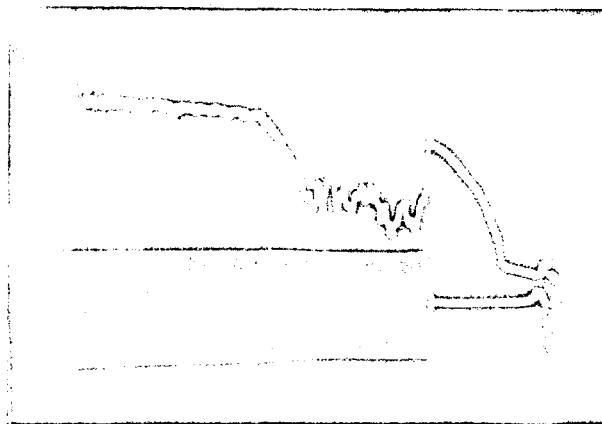


Figure 6

Ion Current for Probe (Lower Ray) and High-Frequency Voltage
for $H = 5.6$ kg force and $j = 20$ a/cm.

4. Discussion of Results

Our experimental data permit us to conclude that heightened diffusion of particles across the magnetic lines of force occurs in a plasma heated by a high-frequency field, at a frequency close to ion cyclotron frequency, if the high-frequency field amplitude exceeds a certain critical value. The coefficient of this diffusion is considerably larger than that of ambipolar diffusion across a magnetic field with the same plasma parameters. In fact, as shown by computations made for the conditions of Figure 3, for $j = 8$ a/cm ($p = 5 \times 10^{-3}$ torr; $T_e \approx 1$ ev; $n = 7.6 \times 10^{12}$ cm $^{-3}$; $H = 5.6$ kg force), this ambipolar diffusion coefficient must be approximately 20 cm 2 sec $^{-1}$. The Bohm diffusion coefficient equals 10^3 cm 2 sec $^{-1}$ in order of magnitude. The magnitude of the diffusion coefficient, estimated on the basis of the plasma decay time, amounts to not less than 5×10^4 cm 2 sec $^{-1}$.

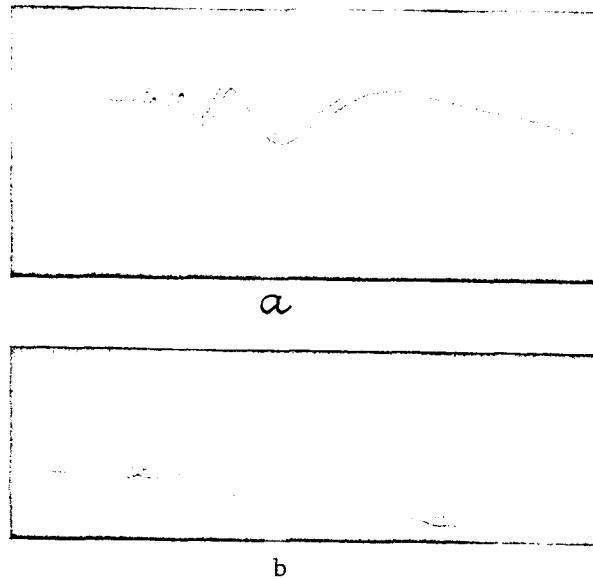


Figure 7
Interference Signal for (a) "Quiet" Plasma ($j < j_c$)
and (b) for $j > j_c$.

In examining the pulse shape of the ion saturation current at the probe, we may conclude that anomalous diffusion is associated with conversion of the plasma into a turbulent state with a broad oscillation spectrum.

Proceeding from relationship, derived experimentally for high /151 pressures, we may assume that anomalous plasma diffusion occurs when the ion drift rate across a magnetic field, under the influence of a high-frequency azimuthal electric field, reaches a certain critical value. This is possibly associated with "beam" instability. In this connection, it is relevant to estimate the directed velocity acquired by ions in a high-frequency azimuthal field when $j \approx j_c$.

By way of an example, we will examine the conditions under which

the relationships depicted in Figure 3 were obtained ($p = 5 \times 10^{-3}$ torr; $n = 7.6 \times 10^{12} \text{ cm}^{-3}$; $j = 2.2 \text{ a/cm}$; $T_e \approx 0.2 \text{ ev}$). Under these conditions, the high-frequency power absorbed by the plasma does not exceed 10^{-1} w/cm^3 , and the difference between ion and electron temperature is small, so that we may assume $T_i \approx T_e$. Assuming $\sigma = 5 \times 10^{-15} \text{ cm}^2$, where σ is the effective cross-section of ion collisions with neutral atoms, we obtain a value of 10^6 sec^{-1} for the effective frequency of ion-neutral collisions. The effective frequency of ion-electron Coulomb collisions is also 10^6 sec^{-1} . We then obtain $5 \times 10^{-7} \text{ sec}$ for the mean interval between two ion collisions.

In order of magnitude, the electrical eddy field strength in a plasma for the radius $r = 3.0 \text{ cm}$ is $E_\phi \approx 10^{-9} \pi r \omega j_c \approx 1 \text{ v/cm}$. The velocity acquired by an ion in this field between two collisions under resonance conditions is $4 \times 10^5 \text{ cm/sec}$, and in order of magnitude, is comparable to the mean thermal ion velocity. This also points to the possibility that "beam" instability will occur [the formation of "beam" instability occurring in cyclotron heating, as a result of the relative motion of ions and electrons in an ion cyclotron wave field, has been studied by Kurilko and Miroshnichenko (Ref. 10) and Stepanov (Ref. 11)].

In conclusion, we would note that the same phenomena may also occur in the works (Ref. 2, 3, 4), where the high-frequency field strengths exceed those in our experiments by at least an order of magnitude. When great, high-frequency power is fed to an incompletely ionized plasma, the rapid heating of this plasma leads to intense

ionization of the neutral gas, thus to a considerable degree balancing the accelerated decay effect caused by anomalous diffusion. Apparently this explains the fact that, in the experiments of Hooke et al. (Ref. 2), the plasma decay rate decreases when a density is reached in the discharge which is optimum for ion cyclotron wave generation. In the experiments of Nazarov et al. (Ref. 3), the discharge tube diameter was smaller than that used by Hooke, but the high-frequency power introduced per volume unit was larger. For these reasons, plasma decay from anomalous diffusion must occur more rapidly under conditions of (Ref. 3) than under the conditions of (Ref. 2). Plasma "disappearance" from the discharge chamber sets in after complete "burn-up" of the neutral gas.

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